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Gravel beaches nourishment: Modelling the equilibrium beach profile

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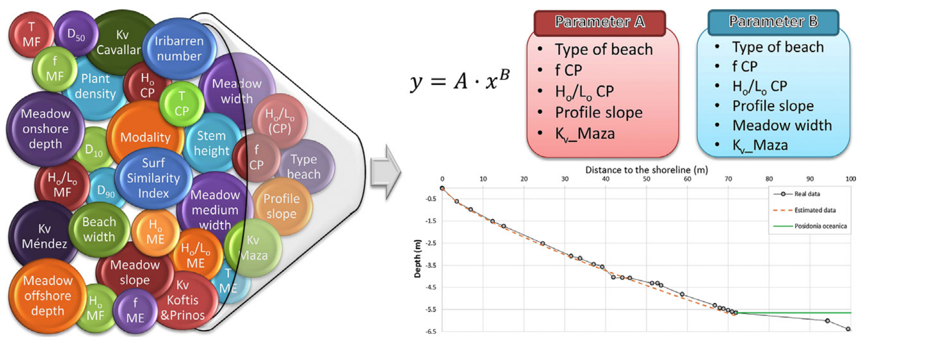
HIGHLIGHTS

- Study of the variables that influence on the equilibrium beach profile on gravel beaches
- Equilibrium profile modelling of 51 beaches of Alicante and Murcia (Spain)
- Numerical model for gravel beach profile in areas with *Posidonia oceanica*

GRAPHICAL ABSTRACT



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ABSTRACT

The erosion of the world's coasts and the shortage of sand to mitigate beach erosion are leading to the increasingly common use of gravel for coastal protection and beach nourishment. Therefore, in order to determine the amount of gravel required for such actions, it is important to know perfectly the equilibrium profile of gravel beaches. However, at present, this profile is obtained from formulas obtained mainly after channel tests, and therefore most of them do not adapt to the real profiles formed by gravel beaches in nature. In this article, 31 variables related to sedimentology, waves, morphology and marine vegetation present on the beaches are studied to determine which are the most influential in the profile. From the study carried out, it is obtained that these variables are the steepness and probability of occurrence of the wave perpendicular to the coast, the profile starting slope (between MWL and −2 m), the energy reduction coefficient due to *Posidonia oceanica* as well as the width of the meadow. Using these variables, different numerical models were generated to predict accurately the gravel beach profile, which will lead to a saving in the volume of material used in the order of 1300 m^3/ml of beach with respect to current formulations, and a greater certainty that the beach nourishment carried out will have the desired effect.

1. Introduction

Gravel beaches are an important form of coastal natural defence (Lopez De San Roman Blanco, 2003; Poate et al., 2013), due to the characteristics offered by this type of sediment, such as hydraulic roughness and permeability (Van Wellen et al., 2000), or their natural ability to dissipate large amounts of waves energy (e.g., Aminti et al., 2003; Johnson, 1987). As a result, beach nourishment with coarse-grained material or a mixture of sand and gravel is becoming more and more frequent (Mason et al., 2007). It is important to highlight the economic implications that the choice of the equilibrium profile has on these beach nourishment. Since it has been observed that bad designs can cause the rupture of the berm and the consequent overflowing of waves during

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extreme events, producing high social costs in the form of damage to coastal properties and infrastructure, flooding of the hinterland and loss of human life (Mccall et al., 2015), hence the importance of good design.

In order to successfully predict the dynamic behaviour of gravel beaches, it is necessary to identify and represent the equilibrium of key processes that control sediment dynamics in the swash zone (Puleo et al., 2000). It is important to understand that the balance of the processes governing this behaviour is different from that of sandy beaches, where, for example, infiltration is negligible (Baldock and Holmes, 1997). In general, during surf conditions, on gravel beaches, sediment is carried upwards where it spreads and deposits in the form of a berm at the top of the beach; this also leads to a steeper slope of the beach face (Austin, 2005; Carter and Orford, 1993; Jamal et al., 2014). This foreshore accretion and increase in beach face slope are against the force of gravity, which requires either the uprush and backwash velocities, or the amounts of sediment transported between uprush and backwash, to be asymmetric (Aagaard and Hughes, 2006).

The complex processes associated with gravel beaches make it difficult to predict accurately morphological changes. Various approaches to variable complexity modelling have been reported, which were generally adopted to describe model families from 1 to 3-D. That is, models that cover a single parameter or element (winds (Benetazzo et al., 2012); hydrodynamic processes (Perlin and Kit, 1999; Saengsupavanich et al., 2008); sediment transport (Fredsoe et al., 1985)); or models that merge several numerical models into one (Bonaldo et al., 2015). These include parametric models (e.g., Powell, 1990) and process-based models (e.g., Clarke et al., 2004; Jamal et al., 2014; Masselink and Li, 2001; Pedrozo-Acuña et al., 2006). Thus, authors like Powell (1990), Van der Meer (1988) or López et al. (2016), suggest a power function for the equilibrium profile of gravel beaches, specifically for the area between mean water level (MWL) and step (Eq. (1)).

$$h = Ax^B \tag{1}$$

Regarding the value of parameter A, many authors have also proposed formulations to obtain it on sandy beaches, such as Dean (1977), Moore (1982), Bodge (1992) and Pilkey et al. (1993), which they consider to be exclusively dependent on the median sediment size (D_{50}). However, there are authors such as Stockberger and Wood (1990) that doubt the dependence between profile and sediment size. In turn, Boon and Green (1988) states that in addition to sediment size, parameter A must be influenced by wave energy. More recent authors such as Turker and Kabdasli (2006) developed a formulation with terms increasingly complex and difficult for the coastal engineer to handle, introducing the effect of energy dissipation by breaking waves in their formulation.

At present, the only empirical or parametric models available for obtaining parameters A and B for coarse-grained profiles are Powell's (1990) and Van der Meer's (1988), based on extensive channel-scale testing (small scale with anthracite for Powell's profile and large and small scale with gravel for Van der Meer's). Van der Meer (1988) proposed a value of 0.83 for parameter B and Eq. (2) for parameter A.

$$A = \frac{h_s}{(-l_s)^{0.83}} \tag{2}$$

where:

$$h_s = 0.22 \cdot \left(\frac{H_s}{L_o}\right)^{-0.3} \cdot H_s \cdot N^{0.07} \tag{3}$$

$$l_s = \left(\frac{H_o \cdot T_o - 180}{3.8}\right)^{1/1.3} \cdot D_{n50} \cdot N^{0.07} \tag{4}$$

and N is the number of storm waves, D_{n50} is the nominal diameter defined as $(W_{50}/\rho_a)^{1/3}$. W_{50} is the value of 50% of the mass in the distribution curve and ρ_a is the density of the material.

Powell (1990) proposed two equations for parameters B (Eq. (5)) and A (Eq. (6)).

$$B = n_2 = 0.84 - 16.49 \cdot \left(\frac{H_s}{L_m}\right) + 290.16 \cdot \left(\frac{H_s}{L_m}\right)^2 \tag{5}$$

$$A = \frac{h_t}{(P_t)^{n_2}} \tag{6}$$

where

$$P_t = 1.73\left(\frac{H_s \cdot T_m \cdot g^{1/2}}{{D_{50}}^{2/3}}\right)^{-0.81} \cdot \frac{H_s \cdot L_m}{D_{50}} \tag{7}$$

$$h_t = H_s \cdot \left[-1.12 + 0.65 \cdot \left(\frac{{H_s}^2}{L_m \cdot D_{50}}\right) - 0.11 \cdot \left(\frac{{H_s}^2}{L_m \cdot D_{50}}\right)^2\right] \tag{8}$$

These formulations mainly depend on the median sediment size (D_{50}), as well as significant wave height (H_s), mean wavelength (L_m) and mean period (T_m).

On the other hand, uncertainty in the data collection of the parameters that are considered as inputs must be taken into account, e.g. where sediment samples should be taken to determine the median grain size (D_{50}) or the type of wave to be used (deepwater, shallow water or breaking wave) or the direction of the wave. An inappropriate choice of these variables implies uncertainties in the definition of parameters A and B and large errors in the final shape of the designed beach.

Therefore, the objectives of this study are: i) to analyse the variables that may affect the equilibrium profile of gravel beaches. ii) Develop a methodology that allows us to select the most important variables. iii) Define and test a model that allows us to obtain parameters A and B proposed by López et al. (2016) for the profile between the mean water level and the *Posidonia oceanica* meadow, which were obtained through field measurements.

2. Study area

The study area includes 51 gravel beaches located in the provinces of Alicante and Murcia (Spain). It is a micro-tidal zone where the astronomical tides oscillate between 20 and 30 cm, and together with the meteorological tides can reach up to 75 cm (Ecolevante, 2006; EcoMAG, 2009).

In the province of Alicante, we find 34 gravel beaches, which are located mainly in the northern part of the province (Fig. 1a). It is the most mountainous area of the province where the coastal landscape is formed mainly by rocky cliffs and small coves. From north to south, the terrain passes from large limestone cliffs to small gravel and silt cliffs.

In the province of Murcia, the 17 gravel beaches are located in the southwestern area (Fig. 1b), where we find mainly cliffs with small beaches. In this area, along with the province of Alicante, there are important extensions of *Posidonia oceanica* meadows.

3. Methodology

The following section describes the process used to select the variables that influence parameters A and B of the power function of the gravel beach equilibrium profile obtained by López et al. (2016) for the area situated between the mean water level and the *Posidonia oceanica* meadow. Secondly, the procedure followed for modelling them is explained.